DOCUMENT RESUME

ED 171 544 SE 027 637

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TITLE Conceptualizing the Structures Underlying Cognitive Behavior - The Usefulness of "Frames".
PUB DATE 79
NOTE 19p.; Paper presented at the annual meeting of the American Educational Research Association (San Francisco, California, April 8-12, 1979)

EDRS PRICE MF01/PC01 Plus Postage.
DESCRIPTORS *Cognitive Processes; Educational Psychology; Elementary Secondary Education; *Learning; *Learning Theories; *Mathematics Education; *Research Tools; *Thought Processes

ABSTRACT

This 1979 AERA presentation was the first paper of a symposium reviewing the usefulness of frames in studying mathematical thinking. The study of the learning of mathematics in 1979 is contrasted to the study of mathematics learning before 1960, the difference being attributed to the development of the discipline of cognitive science. The focus of the paper is on the interpretation of observed behavior in terms of metaphoric models of human information processing. (MP)

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Conceptualizing the Structures Underlying Cognitive Behavior - The Usefulness of "Frames"

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Mathematics Learning Studies Twenty Years Ago

The study of the learning of mathematics in 1979 is very different from the study of mathematics learning in, say, 1960. The change is due largely to the development, in the intervening years, of the discipline of cognitive science, for example in the work of Minsky, Papert, Schank, Michie, Rumelhart, Ortony, Winograd, and others. In 1960 (or thereabouts) it was commonly argued that "one can't know about what's in people's minds," and hence that the study of learning must deal only with "observable behaviors." Learning itself was commonly defined as "a change in behavior." The interpretation of observable phenomena was cast in terms of real-valued numerical variables, such as I.Q. scores, or various sub-scores on achievement tests.

Opponents of this point of view argued that it represented a distortion of "science," that it did not reflect what one really cares about in the learning of mathematics, and that typical results lacked the specificity that would make them useful for most practical purposes.

The guidelines being proposed for the proper study of mathematics learning differed substantially from those that had shaped the fruitful study of chemistry and physics, as one sees at once from the history of those subjects. Appendix A reproduces a few excerpts from commonly used chemistry texts, that

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illustrate clearly the important role played by such metaphoric models as "atoms," "molecules," "collisions," etc. Especially striking is the case of the neutrino, a postulated particle not derived from direct observation of any kind whatsoever, and characterized by properties (possessing both energy and spin, yet having zero mass) that were logically contradictory. Physicists did NOT construe their subject as the study of needles and dials - which is what they observed - nor even as graphs representing functional dependence and correlations. The heart of physics and chemistry has long been seen as the careful elaboration of an extended metaphoric model, which has experienced continuing modifications as a result of continuing analysis and continuing experimentation. Without the initial ping-pong ball metaphors, the inquiry could not have proceeded. It is interesting to note that for 2,000 years the atomic model showed little further elaboration, but in the past 200 years it has been completely transformed and unquestionably lies at the heart of modern physics and chemistry. So, those sciences can surely NOT be said to have followed the guidelines that, in 1960, were proposed for the study of learning.

That learning, defined as "a change in behavior," does NOT reflect what we ordinarily care about becomes clear as one considers examples. When Galileo conceded that the earth stood still, did his change in behavior accurately picture what he had learned? Clearly not, and the same point can be made with examples in anyone's daily life. Perhaps even more than in other fields, mathematics is a matter of ideas that you develop in your own mind. To some extent these ideas are written down on paper, but to quite a considerable extent they are not. To some extent these ideas are verbalized, but to quite a considerable extent they are not.

Finally, critics argued that typical results lacked the kind of specificity

that would make them useful. If your car needs repairs, you do not want to know that it has an effectiveness rating of 83 - you want something which may (or may not) be less quantitative, but which MUST be more descriptive. You want to know, for example, that the distributor cap is cracked, and moisture is getting in and shorting out the ignition spark. Or you want to know that ice crystals in the fuel line are blocking the flow of gasoline to the engine.

The same kind of knowledge is needed to help students learn mathematics. Students themselves are well aware of this need - indeed, the questions most often asked by students include: "Where did I go wrong?" and "What am I doing wrong?" For the error

$$5\ (2x + 3y) = 10x + 3y,$$

the student needs to be told that his error lies in forgetting that the 5 must <u>also</u> multiply the 3y, and not merely the 2x:

$$5\ (2x + 3y) = 10x + 15y.$$

In effect, the student is employing a procedure that contains a "flaw" or "bug," and in order to eliminate the bug he needs to locate it and identify it. There is an error on the student's paper, but it is the flaw in the procedure in the student's mind that really needs correcting.

<u>Recent Studies in Mathematics Learning</u>

Mathematics learning studies in recent years have moved toward answering the main objectives that have been leveled against earlier studies. The need for descriptions of more general behavior patterns - identifying bugs in student procedures - has been addressed in many recent studies, most notably in the work of John Seely Brown. We do not pursue this theme further, but focus instead on another key aspect of recent studies: the interpretation of observed behavior in terms of metaphoric models of human information

processing - the analogue of the physics/chemistry metaphoric models of atoms, molecules, and other particles or aggregates of particles.

Metaphoric Models for Human Information Processing

In our work at Urbana, in studying performances of high-school age students learning algebra and geometry (and some younger students learning arithmetic), we have made use of eleven main hypothetical mechanisms of human information processing, which can be described briefly as follows:

A. Sequential Processes

1. The procedure. A procedure is a definite sequence of steps, aimed at achieving some quite specific result. (Think of it as a human information-processing analogue of a program in a programmable hand-held calculator.) A procedure can relate to other procedures in several ways, the most important being that Procedure A can call upon Procedure B, in order to accomplish part of the assignment of Procedure A. In such a case, Procedure B is said to be a sub-procedure of Procedure A, and A is said to be a super-procedure. A well-known result from Erlwanger's studies of 4th, 5th, and 6th grade arithmetic students is that their arithmetic errors are nearly always located in super-procedures; the various sub-procedures, in the main, tend to be reasonably reliable.
2. The VMS Sequence. Many mathematical tasks have a certain quasi-periodic structure: one sees something, which leads to the retrieval and execution of some procedure; the execution of this procedure yields a modified visual input, which leads to the retrieval and execution of the next segment of procedures, and so on. One thus has a sequence of visual input, procedure execution, new visual input, procedure execution,....Such a pattern is more or less clearly recognizable in, say, a long division problem in

arithmetic, or a "long" multiplication problem, or in the usual written algorithms for multiplying or dividing polynomials. [It is also familiar outside of mathematics, e.g., in driving somewhere if the route is complicated and is relatively unfamiliar. One hopes to recognize a landmark - oh, yes, at that school building one turns right - then to drive along until another key landmark triggers the next key decision and so on. One could not describe the entire route merely from memory, without the prompts given by key visual inputs along the route.] Sequences of this type have come to be called visually-moderated sequences ("VMS" sequences).

3. Successful mathematics students, through practice, are able to develop many VMS sequences into holistic entities which they can contemplate without going through the entire sequence, step by step. (Similarly, our driver becomes able, with practice, to describe the entire route in detail - and hence can instruct others in exactly how to follow the route - without the need to physically re-trace the route in order to prompt his memory.) Sequences which have reached this state are called integrated sequences. [For most present readers, long division is probably an example of an integrated sequence. One can "see the whole process in the mind's eye" - at least in general - without actually writing it down on paper. The specific numerals probably must be suppressed, but the general pattern can be visualized clearly.]

4. But if VMS sequences can be transformed, by practice, into integrated sequences, there must be some mechanisms that make this transformation possible. In particular, there seem to be two easily-recognizable capabilities: a capability to

identify similarities between two portions of procedures, and a "look-ahead" capability to recognize, before-hand, what is coming next. But since carrying out a procedure is itself an experience, quite probably all information-processing capabilities can be brought to bear upon procedures themselves.

5. Clearly, there are record-keeping capabilities. Prominent among these seems to be a record of procedures actually used, as in Winograd's well-known Blocks World.

But our present interest is not in these primarily sequential processes, but rather in something quite different. In studying mathematical behavior (as in studying reading comprehension and verbal behavior), it is difficult to avoid a need for some forms of information-processing that are less sequential and more holistic, that have a more gestalt function. We would argue that an important step forward was taken when Minsky, Schank, Rumelhart, and others introduced the concept of frame, script, or schema. We turn now to hypothetical information-processing mechanisms of this "gestalt" type.

B. Gestalt Processes

6. Frames, Scripts, or Schemata. Although differences are distinguishable between the precise usages of Minsky, Schank, Rumelhart and Ortony, etc., no distinction will be made here, either in name ("frame," "script," or "schema") or in detail description. What is common to all three approaches is far more important than their differences.

Several considerations prompted the introduction of frames. For example, consider the behavior related to "understanding" a written passage, such as:

It was Paul's birthday. Jane and Alex went to buy presents. "Oh look," Jane said, "I'll get him a kite." "He already has one," Alex said. "He'll make you take it back."

Most U.S. adults, having read that passage, can answer questions such as:

Q1: Why are Jane and Alex buying presents?
A1: Because it's Paul's birthday.
Q2: For whom are the presents intended?
A2: Paul.
Q3: Where did Jane and Alex go?
A3: Presumably to a store that sells kites and other things children like.
Q4: The next to the last word in the paragraph - "it" - to what does that refer?
A4: To the kite that Jane was proposing to buy.

Having answered such questions, most humans are surprised to find that not one of those answers is given explicitly in the written passage. The answers have come from the reader's general knowledge of birthdays, presents, stores, etc. In Minsky's language, the reader "retrieved a birthday frame." Frames play an important role, because they embody a representation of a small part of the structure of the world. They are hypothesized to involve variables, with default procedures for assigning values to variables when input data fails to do so. [Asked to repeat the story a week or two later, most adults will unwittingly add to it, by inserting information from the "birthday frames" that was not included in the original story.]

There is a growing body of evidence suggesting the operation of some mechanism generally similar to "frames." The response to natural-language text is among the strongest. In addition to text studies like "birthday," consider also the well-known phenomenon of person A claiming that B told him fact X, when B denies having done so.

(For data specific to mathematics, cf. the study by Hinsley,

et. al., which we discuss below.)

7. Meta-language. Confronted by a problem, a student may need to retrieve one or more frames, and sequence them properly. Possession of appropriate descriptors (a "meta-language") for these frames can help. Consider the problem:

> Find the distance from the origin O (0,0,0) to the plane through the points A(5,0,0), B(0,3,0) and C(0,0,2).

This can be a hard problem, but is not, if one has both the necessary schemata for various parts of the problem, and appropriate descriptors to help get them selected and interrelated. If, for example, one knows that the dot product $\vec{u}.\vec{V}$ between any vector $\vec{V}$, and a unit vector $\vec{u}$ in some special direction, gives us the component of $\vec{V}$ in the direction of $\vec{u}$, one can find any vector from O to the plane (for example, the vector (5,0,0)), and dot it into a unit normal vector. If one has any non-zero normal vector $\vec{N}$, one can get a unit normal vector by dividing $\vec{N}$ by its length. If one has the equation of the plane in the form $ax+by+cz=d$, one easily gets a normal vector $\vec{N}$. And so on. Given descriptors such as these, the problem of selecting and sequencing the necessary schemata becomes entirely manageable.

The distinction between VMS-sequences, meta-analysis, and frame-retrieval is often characterized as the question: are key decisions made early in the consideration of a problem or is decision making distributed throughout the process of working on the problem? Our answer is: sometimes one, sometimes the other, depending upon the individual student and the specific problem. [Cf., for example, the task of integrating $\int \sqrt{x^2+a^2}\ dx$].

Essentially this same conclusion was reached, independently, by Hinsley, Hayes, and Simon [1977]. Our conclusion came from observing thousands of episodes of problem-solving behavior. Theirs came from a particularly elegant sequence of five experiments. In one experiment, for example, it was found that, for some subjects, merely the noun phrase "A river steamer..." was sufficient to trigger the retrieval of an appropriate schema [indicated by the subject saying "It's going to be one of those river things with upstream, downstream, and still water. You are going to compare times upstream and downstream - or if the time is constant, it will be the distance."]. Hinsley, et. al., study mainly older students than we do, and use easier problems, so that they more commonly observe mature schemata, but their results are very close to ours.

8. Clearly there must be some mechanism for determining an appropriate mapping of input data into the <u>variable</u> slots in a frame. This must be one of the most important information-processing functions.

9. Perhaps even more important is the matter of retrieving (if possible) an appropriate frame. The data of Hinsley, et.al., indicate how quickly this is often accomplished. (And any number of situation comedy episodes on TV have depended upon different characters retrieving <u>different</u> frames, with resultant misunderstandings and "double meanings.")

Among the most common errors in all of algebra are errors involving the retrieval of an incorrect frame, as in squaring

$$(2c + \sqrt{(x-a)^2 + y^2})^2$$

to get

$$4c^2 + (x-a)^2 + y^2,$$

whereas what should be retrieved is a frame dealing with

$$(A + B)^2 = A^2 + 2AB + B^2.$$

10. When a frame is selected and retrieved, and when a mapping of input data into frame variables has been attempted, there must be a mechanism for deciding either that the "fit" is a satisfactory one, or else that it is not.

11. Finally, one must consider also the question: where do frames come from? Our observations suggest a sequence generally like this: For novel problems something resembling VMS sequences will be learned (from books or teachers), which - given sufficient practice - will become schemata. Given yet more experience (and perhaps additional explicit instruction), a meta-language will be created. This is the general pattern, though individual students may not complete the entire process, and simpler problems may not require it. [Note that the process is unendingly repetitive, and an elaborate solution initially synthesized by meta-language analysis may become a new VMS sequence, or a new schema]

That is to say, as a VMS procedure is used, perhaps many times, as the experience of using the procedure is subjected to analysis by "look ahead" devices, pattern recognition mechanisms, and (presumably) the whole panoply of information analyzing devices that can be brought to bear on experiences in general, as the VMS procedure is acquiring the wholeness of an integrated sequence, as it is acquiring appropriate meta-language descriptors, it is in fact becoming a frame.

C. How Are Frames Different?

Are frames in fact really different from VMS sequences? We would state at least 5 points of distinction:

1. Frames allow major decisions to be made early in a process, as the study by Hinsley, et. al., demonstrated quite dramatically. Merely the three words "A river steamer....." were sufficient to retrieve a complete frame for that whole category of algebra word problems. Everything that follows is then merely a matter of variable binding confirming correctness of frame and mapping choices, and executing explicit procedures that are referenced by the frame (or are part of the frame).

2. Because of the preceding property, frames make possible "top down" vs. "bottom up" processing. When a frame is retrieved early, it can guide us in looking for that input data which is most essential. Given 2 unknowns, we might seek two linear equations. Given a falling body problem,we can seek initial velocity, etc.

Indeed, having retrieved the "birthday" frame, we can ask: Whose birthday? How old? How many guests? What kind of party? and so on. All such seeking for input data to permit the binding of appropriate variables - all such "knowing where to look and what to look for" - is often called "top down" processing: the schema is itself guiding the data collection.

By contrast, one can have a more minute piece of data, not yet related to any specific "larger" schemata. It is a clue, not a theory. Followed by other clues, it can lead us through some tree, and hence determine the selection of an appropriate "larger" schema. This process is often called "bottom up" processing,

and presumably represents part of the answer to questions about schema selection and retrieval.

The "top down" vs. "botton up" possibilities require not only the existence of frames, but in fact the existence of a very large number of frames, of different "sizes," some small enough and specific enough to be the generalized cognitive representation of a single clue, and others large enough to represent a reality as large and internally structured as a "birthday" or "a falling-body problem."

3. Frames allow for "random access" variable binding, or other processing, whereas procedures are presumably more sequential. In "birthday," we can ask questions in almost any sequential order, and store the answers via variable binding in the "birthday" frame. There are few, if any, restrictions on the sequential order of proceeding. We can ask first: Whose birthday? Or we can ask first: Will there be a party? Or we can ask first: Who are some of the guests? and so on.

4. Of course, of the greatest importance is the question of default values for variables. If I say "Leslie is a teacher," you can immediately retrieve one (or more) probably relevant frames, and can make immediate default evaluations. I can't predict what default value you have given to Leslie's sex (which, after all, could be either M or F), I can't predict whether your default values represent Leslie as a bearded guru wearing a white loin-cloth, or as a Hubert-Humphrey-like politician, or as a faculty member at Harvard Law School, or as a football coach, or as a kindergarten teacher. But you are able to make default evaluations, and to modify them as incoming data may require.

5. People probably display more confidence when their data-processing is based on frames than when it is based on VMS sequences or other purely sequential processes. The "authority" of a John Chancellor may come from the fact that his information processing is based on well-developed frames - we say "the news has meaning for him," "he knows what he's talking about." By contrast, a novice commentator would be "feeling his way," and would not give viewers the same impression of depth.

D. Some Examples

1. We have already considered the problem of finding the distance from (say) the point (a,b,c) to the plane through the points (R,0,0), (0,S,0), and (0,0,T).
2. In observing ninth and tenth grade students, we have been forcefully struck by the fact that the best problem solvers solve problems - even relatively novel ones - with great speed and seemingly little analysis. They "just know how to solve them." It is somewhat akin to the way the reader might find the sum

   79 + 2= ?

   very quickly and with no conscious effort at analysis. By contrast, after they have solved a novel problem, strong problem solvers are often lost in thought for surprisingly long periods of time. It is as if the truly creative process occurs after you have solved a novel problem, and are remorselessly pursuing questions about what God hath wrought, making the associations, reconciling the seeming contradictions, identifying the common patterns that will fit this new knowledge securely (and fruitfully) into a much larger body of knowledge. [Incidentally, we believe we are finding references to this phenomenon in Polya, Kilpatrick, and Newell, and have come to call it "The Newell Conjecture."]

3. One can look explicitly for schemata or meta-language analysis in student performance. For example, Davis et al. [1978] reports interview protocols that indicate that the most able ninth graders observed (who had studied some calculus intermixed with their ninth-grade algebra) were able to deal with a complicated VMS sequence not merely as something to do (a "verb"), but also as a thing to discuss and to analyze (a "noun"); this process is aided somewhat if an appropriate meta language is provided (though the most able students can create a meta language without outside help). For example, consider the problem: A ball is thrown straight up so that it reaches a height of 40 feet. How fast is it thrown? The weakest students cannot solve this problem. Somewhat stronger students can solve it, by carrying out an appropriate VMS sequence, following procedures demonstrated in class, but cannot <u>discuss</u> the problem abstractly <u>without actually carrying out each step</u>. The (few) strongest students can discuss and analyze the solution correctly, in detail, without carrying out each step. For example, somewhat paraphrased, here is an actual protocol from a ninth-grade student of high ability:

"From $h''(t) = -32$ ft/sec^2, you can get $h'(t,V_o)$ with an unknown constant V_o. But for h to be a maximum, h' must be zero. The equation $h'(t_{max},V_o)=0$ gives t_{max} in terms of V_0. Integrating $h'(t)$ gives $h(t,V_o)$. Now, for $t=t_{max}$, $h(t_{max},V_o)=40$, and since t_{max} can be expressed in terms of V_o, we can solve for V_o."

[This is not verbatim, but does follow the answer of the student, talking accurately, in detail, about how he would solve the problem - <u>without executing</u> the steps of the actual VMS sequence, and hence without benefit of the sequence of visual cues as the

written solution develops. The student's actual language made use of phrases such as "plug in this expression for t-max," and so on.]

4. As a final example, we are coming to believe that one can sometimes distinguish "performance" frames from "heuristic" frames. Given the problem: prove that two lines l_1 and l_2 are parallel if and only if their slopes, m_1 and m_2, are equal, the first step in several protocols was to prove that, if $m_1=m_2$, then $l_1 \parallel l_2$. But for the second part of the proof one found two quite different approaches. One 10th-grade student assumed $l_1 \parallel l_2$, constructed a "horizontal" transversal, identified congruent angles, constructed congruent triangles, and computed the slopes of each line from these congruent triangles, getting $m_1=m_2$.

   By contrast, an adult mathematician used the device of choosing a point P on l_2, constructing through point P a line l_3 with slope $m_3=m_1$, and citing the parallel postulate to establish that $l_3=l_2$, whence $m_2=m_3=m_1$. He described this as the strategy: "introduce a new entity E_3 having the properties that you hope some entity E_2 has, and then proving that E_3 is actually E_2. He used this strategy in a wide variety of problems, where E_3 might be a line, or problems where E_3 might be a triangle, etc.

   We are inclined to classify the "E_3" strategy as "the use of a heuristic frame," contracted with the 10th grader's strategy, which we would describe as "the use of a performance frame." Both seem frame-like, but the 10th grader's solution was more complicated, and made use of very specific, detailed work that had been done during the year. We were struck by

what seems to be the greater simplicity of the adult's solution - not what we had initially expected. But perhaps it is what one ought to expect.

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